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Thermal stratification within the water tank

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ABSTRACT

To sufficiently store and use high-quality heat energy, thermal stratification is gradually applied in many kinds of energy storage fields such as solar thermal utilization system. Because of the unsteady characteristics of solar radiation, thermal storage becomes very essential in long-term operation of heating load. The wide application of thermal stratification lies in the minimization of the mixing effect by use of the thermal stratification, which is caused by the thermal buoyancy because of the difference of temperature between cold and hot water. According to the review, the conception of thermal stratification allows a wide variety of different design embodiments, which essentially extends the fields of practical application of these devices. In this paper a survey of the various types of thermal stratification tanks and research methods is presented, and reasons of energy storage with efficiency problems related to the applications are introduced and benefits offered by thermal stratification are outlined. The structure designs based on theoretical prediction of thermal-stratified water tank performed at many organizations are introduced and are compared with their experimental results. Finally, the development of the tank with thermal stratification in the future application is predicted.

Contents

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Nomenclature

a	thermal diffusivity (m^2/s)
A	cross-section area of stratified tank (m^2)
Bi	Biot number, $Bi = hr_t/k_f$
c	specific heat (kJ/(kg K))
C_p	specific heat of fluid (kJ/(kg K)), $c_p^* = c_p/c_{p_0}$
d	diameter of the inlet (m)
D	diameter of the storage tank (m)
Fr	Froude number, $Fr = u/(lg)^{1/2}$
g	gravitational acceleration (m/s^2)
g^*	gravity acceleration (m/s^2), $g_y^* = g_y/g$
Gr	Grashof number, $Gr = g\beta(T_i - T_\infty)r_t^3/v^2$
h	heat transfer coefficient ($W/(m^2 K)$)
J	number of water layers
l	height of cylindrical tank (m)
L	dimensionless height of cylindrical tank, $L = 1/r_t$
m	number of bottom missed layer in the tank
n	time step
p	pressure (Pa)
P^*	dimensionless pressure, $P^* = p/\rho_0 u_0^2$
Pe	Peclet number, $Pe = Re\,Pr(u_i r_t/a_f)$
Pr	Prandtl number, $Pr = v/a_f$
r	radial coordinate (m)
s	distance of baffle from the inlet (m)
S	dimensionless distance of baffle from the inlet, $S = s/r_t$
t	time (s)
T	temperature (K)
$T(i,0)$	initial temperature field in the tank
$T(i,n)$	temperature of the ith fluid layer at time step n
T_c	temperature of cold water (K)
T_h	temperature of hot water (K)
T_i	inlet temperature (K)
T_{in}	initial temperature (K)
T_{mix}	mixing tank temperature (K)
T_∞	ambient temperature (K)
u	velocity in x-direction (m/s)
u_0	initial inlet velocity (m/s)
u_i	inlet velocity (m/s)
u^*	dimensionless velocity in x-direction, $u^* = u/u_0$
$v$velocity in y-direction (m/s)	
v^*	dimensionless velocity in y-direction, $v^* = v/u_0$
V	volume of tank (m^3)
$V(i)$	volume of the ith fluid layer (m^3)
ΔV	volume of the cold water entering during the time interval Δt (m^3)
x^*	dimensionless length, $x^* = x/L$
y^*	dimensionless length, $y^* = y/L$
z	direction along tank height (m)

Greek symbols

$\alpha_1(i)$	thermal conductivity (W/(m K))
$\alpha_2(i)$	heat loss coefficient ($W/(m^2 K)$)
β	coefficient of thermal expansion (1/K)
β_0	coefficient of thermal expansion at T_0 (1/K)
β^*	dimensional coefficient of thermal expansion, $\beta^* = \beta/\beta_0$
θ	dimensionless temperature, $\theta = (T - T_\infty)/(T_i - T_\infty)$
λ	coefficient of heat conductivity (W/(m K)), $\lambda^* = \lambda/\lambda_0$
μ	viscosity (kg/(m s)), $\mu^* = \mu/\mu_0$
ρ	density of fluid (kg/m^3)
ρ_0	density of fluid at T_0 temperature (kg/m^3)

Subscripts

*	dimensionless parameter
0	parameter value at temperature of T_0
i	inlet value
st	within the storage
t	at time t
w	tank wall

1. Introduction

If the supply and the exhaust of energy cannot be kept in balance, energy storage will become important for sustainable utilization. This mismatch phenomena generally occurs in the systems with unstable resource or requirement, such as solar energy system, hydraulic power generation, food preservation and so on. Discontinuous changes of solar radiation lead to the variation of solar energy obtained by solar collecting system, also the unstable quantity of food preserved under cooling condition makes different requirements on refrigeration output; these kinds of mismatches derived from need and supply are necessary to be allocated in energy storage devices.

During energy conversion, diverse means can be used to store the redundancy according to the energy forms. As thermal energy be concerned, a number of these devices utilize phase change materials such as eutectic salt, or rock beds as the storage material; the former stores mainly latent heat and the latter stores sensible

heat. However, liquid water with the characteristics of non-toxicity, easy obtainment, high thermal capacity, suitable for wide range temperature requirement is served as the main storage medium in domestic or even industrial utilization; therefore, water tank is widely used in energy storage system for civil use or industrial process. Another reason for wide utilization of water tank is based on the critical effect on balance of energy supply and demand, especially in solar energy systems such as solar domestic hot water (SDHW), thermal energy storage, district solar heating systems, and other unsteady energy used occasionally. Therefore, water tank plays two main important roles as energy reservoir and redistribution.

As far as solar energy system is concerned, from the lower temperature section of the water storage tank, the cold water circulating through the collectors is heated by solar radiation, where it becomes the hot water and returns to the storage tank. If the hot water is allowed to mix with the cold water in the tank, the supplied temperature to the load is lowered and the useful quality of energy is degraded. Also, because of mixing, the whole water temperature in the tank tends to the even, the amount of energy collected may be decreased if the collector inlet fluid temperature is higher than the unmixed storage temperature. Therefore, in order to obtain the maximum efficiency of stored energy, thermal stratification technology is introduced and developed in recent 10 years.

In this paper a survey of the various types of thermal stratification tanks and research methods is presented. Initially, reasons of energy storage with efficiency problems related to the applications are introduced and the benefits offered by thermal stratification are outlined. A mechanics analysis in detail is attempted followed by a description of two main types of stratified tanks including direct and indirect heat transfer. This is followed by exhaustive insights on factors of thermal stratification such as inlet and outlet, baffle plate, thermal insulation material and so on, and next, a description of the methods used to evaluate their performance and evaluating index is presented under different working conditions. Furthermore, from the historical literatures, the structure designs based on theoretical prediction of thermal-stratified water tank performed at many organizations are introduced and compared with their experimental results. Finally, dimensionless groups are introduced to evaluate the thermal stratification performance, which are the integral marks in the structure design and efficiency improvement.

2. Thermal stratification

Thermal stratification phenomenon is mostly concentrated in air or liquid medium. Although temperature stratification of indoor air is studied in many literatures [1–3], more applications of it are combined with water supply system, especially in solar engineering. The research on thermal stratification within the tank has been studied intensively since the 1970s [4–7], and some analytical simulations of thermal stratification in storage tank were performed by a number of researchers, whose studies showed that thermal stratification can effectively improve the performance of the energy storage.

By a comparison between fully stratified water tank and fully mixed water tank employed in many solar utilization systems [8], it is found that the energy storage efficiency and the whole system may be increased up to 6% and 20%, respectively. For seasonal thermal energy storage, the average net energy and exergy efficiencies can even be improved by 60%. Further essential reasons are analyzed in solar domestic hot water systems. Researchers [9,10] found that thermal stratification, on the one hand, has the effect of decreasing the temperature at the collector inlet which increases its efficiency and, on the other hand, of decreasing the periods of operation of the auxiliary energy supply, so improving efficiency is not only for the water tank, but also for the whole extended system.

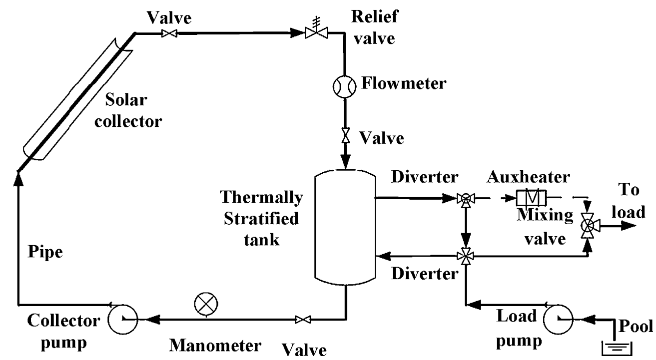

Fig. 1. Schematic diagram of a solar domestic hot water (SDHW) system.

2.1. Building of thermal stratification

Here, a solar domestic hot water system is set as an example. Fig. 1 presents the schematic diagram of a SDHW system, which generally consists of three main parts, namely, solar heating loop, user load loop, and water tank with thermal stratification. The central connection of the two loops is the water tank, while the task of solar heating loop is to generate hot water filled into the storage tank, and the load loop stands for the utilization process of the terminal energy devices such as heat exchanger, air conditioning and other hot water demand equipments.

From the viewpoint of thermal stratification, it is assumed that the inlet fluid will drop to a level where its density matches the density of the surrounding fluid. Due to the gravity and buoyant effect, water with different temperature will deposit the corresponding height according to the density difference; light density will bring hot water to the upper layer, and cold water with heavy density will fall down the bottom layer. Then thermal stratification is built as "the thermal barrier" to separate the warm and cool fluids, and maintain the stable vertical temperature or density gradient.

Stable thermal stratification is necessary to be built and maintained within the water tank, that means, mixing should be minimized in order to obtain maximum energy. An obvious temperature gradient or thermo-cline is then to be formed between hot water at the top and cold water in the bottom. Thermal stratification within the tank can be achieved by several methods [11]: (1) heating of vertical walls which results in the creation of hot thermal boundary layers drawing hot fluid into the upper part of the tank; (2) heat exchange between the fluid contained in the tank and that circulating in a heat exchanger carefully placed inside or outside the tank; (3) direct inlet into the tank of hot fluid at suitable heights.

2.2. Destruction of thermal stratification

If the cold water flows downward and entrain warmer fluid in the tank, mixing and the destruction of thermo-cline will then be occur. Usually, this effect is generally realized to local within a small horizontal region near the inlet port, but under favorable conditions, mixing may extend to include most of the tank volume. The motion generally takes place in a thermal storage tank combining the effects of forced and natural convections.

During the operation, fluid extracted from the bottom of the tank is usually heated and returned to the top of the tank.

Simultaneously, a second circuit may be used which extracts warmer water from the top of the tank to supply a load, and injects cold water at an equal flow rate delivering to the bottom of the tank. As well as the downward cold water, turbulence generated during these operations will also cause mixing and destruction of thermal stratification.

Earlier investigations [12–16] showed that stratification in thermal storage tank is mostly due to multiform factors, such as inlet mixing and conduction along tank walls. More latter researches specialized in thermal stratification research developed different models to investigate the performance of the thermal storage system, and their results showed the stratification degree depends mainly on tank configurations and operation conditions. For inconsistent criteria being adopted, these researchers attained different results.

2.3. Stratification within water tank

The stratified water tanks are conventionally classified into two types: indirect and direct heating mode. For the indirect heating water tank, several heat exchanger configurations have been employed and the following configurations are among the most common: (1) immersed tubes or immersed coils in the tank; (2) external shell-and-tube exchanger; (3) mantle heat exchanger with a narrow annular jacket around the storage tank.

For indirect heating water tank, because of the temperature difference between the hot section and the cold section within the tank, water can be easily kept in thermal stratification state due to natural convection, but energy efficiency between two separated media will be decreased due to insufficient heat transfer. While for direct heat transfer water tank, thermal stratification will be more easily destroyed by water turbulence.

2.3.1. Indirect heat transfer

Heat exchanger is the main characteristic of the indirect heat transfer type, which may be placed inside or outside the tank as shown in Fig. 2. Three kinds of exchangers, namely, immersed coils, external shell-and-tube, and mantle heat exchanger, are introduced here.

2.3.1.1. Immersed exchanger. On heat transfer efficiency of load-side immersed heat exchangers, earlier studies on testing and analysis in solar domestic hot water systems was done by Farrington and Bingham [17]; they reported that a smooth coil with only 70% of the surface area of a finned coil performed better than the finned coil. Also, load-side heat exchangers can maintain and enhance stratification in storage tanks, permitting the use of control strategies that take advantage of stratified storage tanks to increase system performance. Increasing the heat exchanger flow rate and area resulted in higher heat transfer rates but not necessarily optimal performance; lower initial tank temperatures resulted in reduced tank stratification; the smooth heat exchanger outperformed the finned heat exchanger with the same outside surface area.

In comparison with these considerations, a further research on domestic hot water store with immersed exchanger is performed by Spur et al. [18,19]; the simulation results were validated by measurements obtained from experiment, and the conclusion showed that the inner configurations of the tank and the immersed heat exchanger can significantly affect the store performance; the stratified store can improve up to 32% more efficiency than the common commercial available store.

In their experimental study, three different stores were used as shown in Fig. 3. Store A is the novel-stratified store, which is chosen in order to determine the effect of an improved inner store design on the performance of the store. Store B contains a heat exchanger which is coiled upward from the bottom to the top of the store. Store C contains a heat exchange which is coiled upward from the bottom to the top of the store and downward from the top to the bottom of the store. Store C achieved less stratification compared with those in stores A and B. The maximum temperature difference between the top and the bottom of the store C hardly reached 8 °C, whereas in stores A and B, stratification temperature differences of about 15 °C occurred. The sophisticated inner configuration of the novel store improved its performance by up to 15%. The store with the downwards coiled heat exchanger pipe showed adverse effects and a decreased performance by up to 20%.

According to these conclusions, the inner arrangement of the immersed heat exchanger and type of conduct pipe significantly affect the stratification along the store height, the heat transfer and the recovery process of the immersed heat exchanger. The immersed heat exchanger position should be coiled upwards and located in the upper part of the tank in order to achieve a high rate of heat extraction.

2.3.1.2. External exchanger. Structure in detail is shown in Fig. 4, the solar liquid flows through the primary side of an external plate heat exchanger. For charging the store, shown in Fig. 4a, a second circulating pump draws cold water from the bottom of the store, this flows through the secondary side of the heat exchanger in a counter-flow and then flows back into the middle of the store. An external heat exchanger has better thermal transfer properties than an internal type. Stratified charging system with a three-way valve at two different heights is shown in Fig. 4b [20].

Parent et al. [21] analyzed a shell-and-tube heat exchanger external to the tank, in that the natural convection loop involves the tank water, not the collector fluid, and is driven by the density difference due to stratification in the storage tank. This configuration may be more practical than the immersed coil type, and there is less mixing to degrade the thermal stratification. Their analysis was based on two theoretical models and some experiments. For the configurations they investigated, the heat exchanger effectiveness ranged from 40 to 99%.

Further work has been done in characterizing this type of natural convection heat exchanger for use in solar water heaters by Fraser et al. [22] and Dahl and Davidson [23], who defined external heat exchanger performance in terms of the natural convection

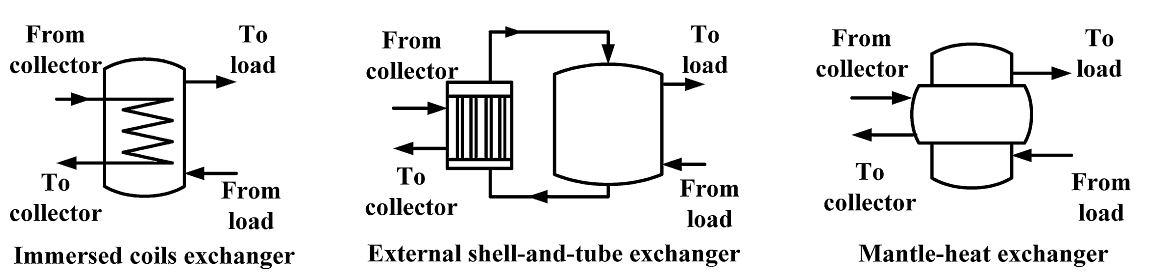

Fig. 2. Heat exchange between the fluid contained in the tank and that circulating in a heat exchanger carefully placed inside or outside the tank.

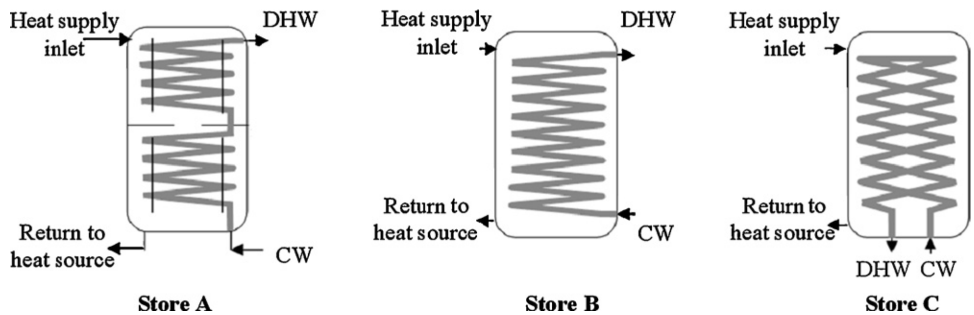

Fig. 3. Schematic design of stores A, B and C as used in the analysis [18,19].

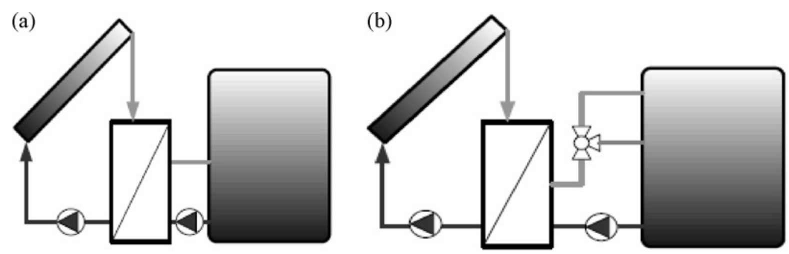

Fig. 4. Two types of external exchanger used in thermal stratification tank [20]: (a) external heat exchanger and (b) external heat exchanger with bypass circuit.

flow rate. If the temperatures and flow rate are known the heat transfer to the tank, the place where it is transferred can be determined.

2.3.1.3. Mantle heat exchanger. The mantle heat exchanger configuration provides a large heat transfer area and a desirable solar collector fluid flow pattern in the mantle, which makes the mantle heat exchanger as one of the simplest and cheapest ways of producing high heat exchanger effectiveness in promoting thermal stratification. The advantages of the mantle heat exchanger design are: (1) simplicity of design due to the combination of the hot water tank and heat exchanger into one unit; (2) larger heat exchange surface area (e.g. if a mantle heat exchanger was used in the study by Webster et al. [24], instead of the eight immersed copper tubes, the heat transfer area would have been at least two and a half times larger); (3) higher efficiency. Furbo [25] compared three low flow solar water heating systems with heat exchangers and found that the vertical mantle type outperformed the immersed coil and external shell-and-tube types. The two main structures analyzed in literatures are listed in Fig. 5.

Investigations of horizontal mantle heat exchangers have been made by Buenconsejo [26], using flow visualization and by Nasr et al. [27] by computational modeling. Results have shown that when the inner tank is stratified, recirculation zones form in the annular heat exchanger space which causes more heat to be transferred to the bottom of the tank, thus decreasing the tank stratification. Although the flow in a horizontal mantle heat exchanger is not dominated by free convection, buoyancy forces have been shown to alter the flow field thus indicating that the flow is in the mixed convection regime.

Baur et al. [28] studied vertical mantle heat exchangers for pumped circulation solar water heaters. Based on their experimental data they concluded that there was little difference in annual performance between vertical mantle and external heat exchanger solar water heaters. Also results form Shah et al. [29] showed that most of the incoming mantle fluid seeks the thermal equilibrium level in the mantle, and thermal stratification in the mantle and the inner tank is not disturbed.

Knudsen et al. [30,31] investigated the flow structure and heat transfer in both the mantle and in the inner tank for both hot and warm inlet temperatures to the mantle and for both initially stratified and initially mixed inner tank. This study demonstrates that a vertical mantle heat exchanger is able to promote stratification in the inner tank even when the mantle inlet temperature is lower than the tank temperature at the input. Further numerical studies on local heat transfer performance are done [32–35], More researchers [36–40] used PIV and computational fluid dynamics (CFD) to investigate the flow structure in the mantle.

2.3.2. Direct heat transfer

For the direct heating water tank, in order to inhibit the turbulence generated from the mixing of the hot and the cold

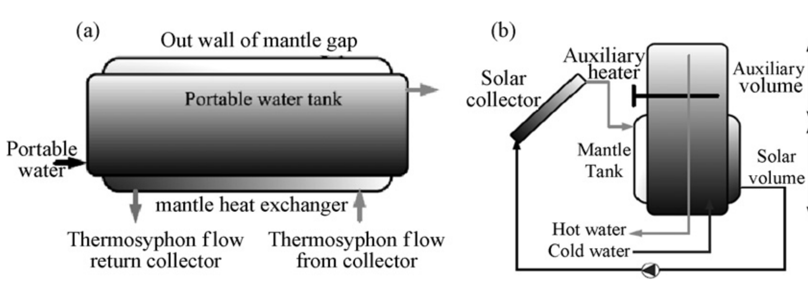

Fig. 5. Two types of mantle tank used in solar thermal stratification [25].

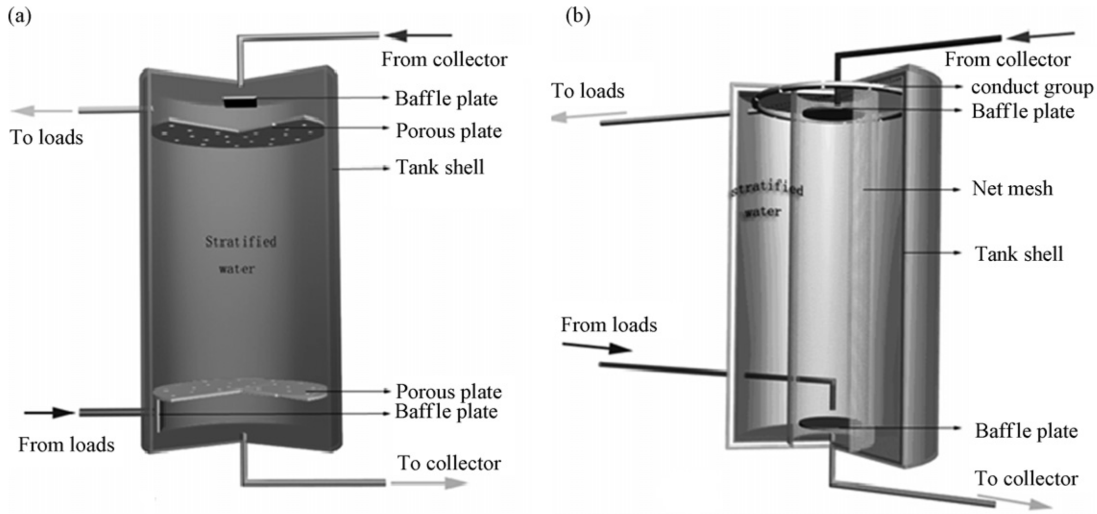

Fig. 6. Structure and schematic design comparison between the two types of tanks with thermal stratification: (a) baffle plate applied within the tank and (b) porous structure applied in the tank.

water, several measures are taken, such as adding baffle plate (Fig. 6a) at the inlet of the tank, porous mesh (Fig. 6b) to slow up the water flow, and Fig. 6 shows the schematic designs of these two typical water tanks with thermal stratification. In order to decrease the mixing of the water, besides the above measures, it also allows wide variety for different design in structures, and the dimensional optimizations, etc.

The geometrical factors [4,41–44] of tank include tank size, the aspect ratio of tank, inlet shape of diffuser system, and baffle size and its shape to control flow pattern. Further, the parameters related with operating conditions [45–47] include inlet flow condition such as flow velocity, inlet and initial tank water temperature with difference in temperature, and cyclic periods of loading and discharge. Here the main conclusions are drawn and compared in the analysis of thermal stratification.

3. Analysis on thermal stratification

3.1. Modelling of thermal stratification

Development of mathematical model is one of the important contents to study the thermal stratification within the tank. In this section, the physical mechanism of thermal stratification will be summarized and the major factors obtained from the mathematical model will be described.

3.1.1. Modelling analysis

3.1.1.1. One-dimensional model. Currently, the mathematical models on thermal stratification were mainly developed for two types of thermal storage water tank: a temperature-stratified type and a balanced type. Sagara and Okumiya [48] showed that the model of temperature-stratified type could be modified to be applied to the balanced tank which is a sophisticated temperature-stratified type. Caldwell and Bahnfleth [49] proposed several one-dimensional models on mixing in stratified chilled-water thermal energy storage tanks. In the simplest models, mixing is assumed to be uniform throughout the tank. Other models permit spatial variation of mixing intensity.

The typical physical model is shown in Fig. 7. Along the flow direction, the tank is divided into N equal elements. Table 1 gives a summary on one-dimensional mathematical models. First kind of models is the temperature-stratified model, in which δ plays an important role in determining the position of the incoming flow (Table 1). The water can find the corresponding position according to its temperature value.

The other two kinds of models were built by Alizadeh [50], in which the tank is also divided into 'N' equal volume layers. Cold water is allowed to enter the bottom of the tank and is assumed to mix with the initial 'm' bottom layers. Here, $T(i,n)$is the temperature of the ith layer at time step n and $V(i) = V/k$.

Simultaneously, it has no effect on the water with the position higher than this point, that is, the lower temperature inlet water will have no effect on the hot temperature water, and the mixing process is neglected by temperature-stratified consideration. In the second model, heat leaks from the ambient, conduction through thermo-cline, conduction from warm fluid layers to cold fluid layers through the conducting wall and thermal mixing at inlet and outlet are considered [51].

Analysis solutions can be found in the studies of Yoo and Pak [52]. Al-Nimr [53] studied the conjugate behavior of a hot water storage tank having finite wall thickness, a closed form analytical solution for the temperature field within the tank using Laplace transform technique was used. It was found that the thermal stratification decreases with finite wall thickness, and this effect becomes less apparent at high Peclet Numbers. When another equation based on tank wall heat balance is coupled with the energy equation mentioned above, the dimensions of tank wall can be considered as an impaction to stratification.

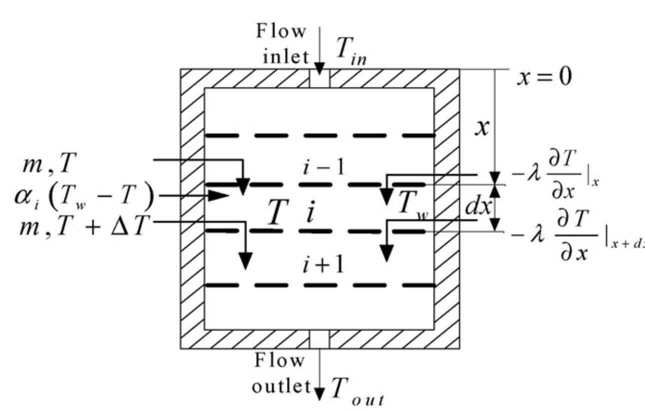

Fig. 7. Physical scheme of thermally stratified tank [49].

Table 1
Typical classification of one-dimensional models

One-dimensional model	Description	Annotation and character
Temperature stratified type [50]	$\frac{\partial T}{\partial t}=\frac{\lambda}{\rho c_{p,s}}\frac{\partial^2 T}{\partial x^2}+\delta\frac{\dot{m}_s}{\rho c_{p,s}}\frac{\partial T}{\partial x}$	$\delta=\begin{cases}0, & T>T_{in}\\ 1, & T\le T_{in}\end{cases}$, δ is used to determine the position of the incoming flow
Heat balance model [50]	$\frac{\partial T}{\partial t}=\frac{\lambda}{\rho c_p}\frac{\partial^2 T}{\partial x^2}-\frac{\dot{m}}{\rho c_p}\frac{\partial T}{\partial x}+\frac{hP}{A\rho}(T_w-T)$, $\frac{\partial T_w}{\partial t}=\alpha_w\frac{\partial^2 T_w}{\partial x^2}+\frac{\alpha_0 P}{A_w\rho_w c_w}(T_\infty-T_w)-\frac{\alpha_s P}{A_w\rho_w c_w}(T_w-T)$	Heat leaks from the ambient, conduction from warm fluid layers to cold fluid layers through the conducting wall and thermal mixing at inlet and outlet are considered
Turbulent mixing model [51]	$T(i,n)=\{[V(i)-(\Delta V/m)]T(i,n-1)+(\Delta V/m)T_{in}\}/V(i),\ (i\le m)$ $T(i,n)=\{[V(i)-\Delta V]T(i,n-1)+\Delta VT(i-1,n-1)\}/V(i),\ (i>m)$ $T(i,n)=\{[V(i)-(\Delta V/m)]T(i,n-1)+(\Delta V/m)T_{in}+\alpha_2(i)T_0$ $+\alpha_1(i)[T(i,n-1)-T(i-1,n-1)]\}/\alpha(i),\ (i\le m)$ $T(i,n)=\{[V(i)-\Delta V]T(i,n-1)+\Delta VT(i-1,n-1)+\alpha_2(i)T_0$ $+\alpha_1(i)[T(i,n-1)-T(i-1,n-1)]\}/\alpha(i),\ (i>m)$	Without consideration on heat loss and the diffusion within the tank Taking the fluid thermal conductivity and the heat loss into account
Displacing mixing model [51]	$T(i,n)=\{[V(i)T(i,n-1)-(\Delta V/mT_{in})]+(i-1)(\Delta V/m)$ $T(i-1,n-1)\}/[V(i)+i(\Delta V/m)],\ (i\le m)$ $T(i,n)=\{[V(i)-\Delta V]T(i,n-1)+\Delta VT(i-1,n-1)\}/V(i),\ (i>m)$	It is assumed that at commencement of the cold inflow of the inlet water is equally distributed amongst the initial bottom layers so that no mixing occurs between the layers

Nelson and Balakrishnan [51] found that the effect of thermal stratification increases with the modified Biot number, that is:

$$Bi_m=\frac{h_0L^2}{k_w\delta} \tag{1}$$

Stratification cannot be improved markedly when the aspect ratio of the length and the tank wall thickness beyond 3.0, similarly, not much advantage in thermal stratification is obtained beyond L/d value of 200 for a storage tank irrespective of aspect ratio. Also, for the convenience of the usage, a simple correlation of the efficiency is proposed as a function of the Peclet number in Yoo's work in 1993 [54].

As different method concerned, Davidson and Adams [55] introduced the mix number, based on the height weighted energy, or moment of energy, in the tank, ranges from 0 to 1, with 0 representing a perfectly stratified (unmixed) tank and 1 representing a fully mixed tank. Zurigat and Maloney [56] thought that although various factors affecting the performance of a stratified tank can be accounted for by the higher order models, two- and three-dimensional models, the introduction of empirically based mixing parameters into the one-dimensional models renders them widely applicable and practical in the simulation of energy systems incorporating thermal storage tanks.

However, one-dimensional models cannot describe flow structure in detail within the tank, especially under high flow rate and complex tank structure conditions, backflow generated from mixing and propulsion will destroy the relatively regular stratification which can be described by one-dimensional equations. Therefore, after 1990s, more investigations focusing on two or more dimensional models were developed gradually and a set of new methods analyzing stratification was applied with the developments of hydrodynamic.

3.1.1.2. Two-dimensional model. Thermal stratification is caused by the minimization of the mixing effect of the hot and cold fluids within the tank, while the physical insight of mixing mechanism is controlled by the thermal buoyancy and convective mixing. Numerical approaches by Navier–Stokes equation show that the outline of the mixing process can be examined by using this two-dimensional method. In the following the typical cases on model proposition will be given.

As governing models be concerned, the flow in the tank is normally modelled by using two equations based on consideration of the gravity effect. In Euler orthogonal coordinates, the governing equations can normally be expressed as following and many studies in literatures [57,47,58–60] are based on these governing equations with consideration of gravity effect:

$$\nabla\cdot\mathbf{u}=0 \tag{2}$$

$$\frac{\partial\mathbf{u}}{\partial t}+\nabla(\mathbf{u}\cdot\mathbf{u})=-\frac{1}{\rho}\nabla p+g\beta(T-T_m)+\nu\nabla^2\mathbf{u} \tag{3}$$

$$\frac{\partial T}{\partial t}+\nabla\cdot(\mathbf{u}T)=a\nabla^2 T \tag{4}$$

According to the experimental similarity principle of hydrodynamics and heat and mass transfer, the dimensionless equations are transformed as [61,57]:

- Continuity equation:

$$\frac{\partial(\rho^*u^*)}{\partial x^*}+\frac{\partial(\rho^*v^*)}{\partial y^*}=0 \tag{5}$$

- Momentum equation:

$$\frac{\partial u^*}{\partial t}+\frac{\partial(\rho^*u^*)}{\partial x^*}=-\frac{\partial p^*}{\partial x^*}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2u^*}{\partial x^{*2}}\right) \tag{6}$$

$$\frac{\partial v^*}{\partial t}+\frac{\partial(\rho^*v^*)}{\partial y^*}=-\frac{\partial p^*}{\partial y^*}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2v^*}{\partial y^{*2}}\right)+\mathrm{Ri}\,\theta \tag{7}$$

- Energy equation:

$$\frac{\partial\theta}{\partial t}+\nabla\cdot(u^*\theta)=\frac{1}{Re\,Pr}\nabla^2\theta \tag{8}$$

The upper dimensionless equations group is normally used to facilitate the numerical treatment and allow better comparison between the different methods of solution and also with available experiment results. The forms of these equations may be shown in different representations under different assumptions and coordinate system, the basic content is assumed that viscous dissipation is negligible and the working fluid is incompressible. The thermophysical properties are constant, except for the density variation with temperature for using the Boussinesq approximation. Other researches on thermal stratification with different models investigate the performance of the thermal storage system [62].

3.1.2. More considerations on model

Three-dimensional models are also used to evaluate the effect of storage tank geometry on performance by Eames and Cònsul

[63,64]. CFD simulation is a useful tool to solve the three-dimensional models and more references by using CFD to attain solutions can be found in recently investigations [65–67].

New structural thermal-stratified water tank is still on design and optimization with the further development of the coherent technology. In order to reproduce the temperature field in the tank, TRNSYS's TYPE 60 and 140 are used to analyze the large solar system and fluid motion [68]. The experiments of Klein et al. in 1996 were compared with simulations carried out with TRNSYS's Types 60 and 140 [69]. According to their results, differences are noted in both scenarios probably due to mixing hypothesis and convective resistance which are not taken into account; more attentions onto stratification which are very important to energy performances are focus on the CFD simulations, that is, the detailed stratification over reasonable simulation time should be constructed by developing a zonal model because a layer is not at uniform temperature level.

3.1.3. Limitations of simulations

Thermal stratification is also complex physical process affected not only by geometrical structure, but also operation conditions which cannot be described in the modeling. Additionally, it is possible to model a system to a high degree of accuracy in order to extract the required information. In practice, however, it may be difficult to represent in detail some of the phenomena occurring in real systems.

Although a number of advantages can be offered by simulations as powerful tools in the previous sections; however, there are many limits in their use for the disadvantages of making mistakes. For example, if the assumptions are based on erroneous constants or neglect factors, the results obtained will not access to the real values. Also in many engineering calculations, a high level of skill and scientific judgment is required in order to produce correct and useful results [70].

3.2. Influencing factors analysis

The geometrical factors [4,41–44] of tank include tank size, the aspect ratio of tank, inlet shape of diffuser system, and baffle size and its shape to control flow pattern. Further, the parameters related with operating conditions [45–47] include inlet flow condition such as flow velocity, inlet and initial tank water temperature with difference of temperature, and cyclic periods of loading and discharge. Here the main conclusions are drawn from the following effects.

3.2.1. Geometrical structure

3.2.1.1. Inlet and outlet effect. The flowing pattern will be affected by the geometry structure at inlet and outlet points when water flows in or out of the water tank, such as the diameter, the installation position, buffer plate, etc. Lavan and Thompson [4] carried out an experimental investigation to determine the effect of geometric and dynamic parameters on thermal stratification in a vertical hot water storage tank. It was found that the inlet location had a strong influence on thermal stratification while the location of the outlet was much less important. Also Al-Najem and El-Refaee's [71] investigation showed that the turbulent mixing (or eddy conductivity) factor caused by hydrodynamic disturbances at the inlet and outlet ports of storage tank plays an important role in the performance of thermal stratification storage tanks.

The tank inflow situations include two configurations: the upper inflow and the lower inflow. The inlet hot water form collector enters tank from the top will easily build stratification for matching the result of natural convection, but colder inflow at the top of tank will completely mix up the temperature field inside the tank. Zachár et al. [72] studied two different inflow situations: firstly, the upper inlet flow with a flat plate situated opposite to the inlet and secondly, the lower inflow configuration with similar arrangement. The conclusion showed that the top of the tank has a significant effect on the stratification when cold water enters form the top of tank.

Eames and Norton [73] indicated that the gained energy is 5.25% higher than a fully mixed tank with this flow rate conducing to a stratified tank. Their experiment shows that if the inlet jet does not impinge directly on the store walls, either as result of diffusion or buoyancy forces, for hot water stores with constant horizontal cross-section, it is apparent that the store cross-sectional geometry had little effect on the store stratification performance. Also revealed is that a single inlet port with variable inlet temperature jet leads to poor store charging performance, enhanced performance could be achieved by having a range of ports at different height, the inlet fluid entering the store at the height at which the resident store fluid temperature most closely matches the inlet fluid temperature.

Earlier researchers [74,75] devoted their attention to the mixing introduced by the fluid inlet flow, which will lead to de-stratification of a thermal storage tank. Various inlet configurations were examined experimentally by Carlsson [76] and the optimal flow rate through a solar hot water system was studied by Matrawy and Farkas [77] in case of direct inflow. Furbo et al. [78] indicated that if two draw-off levels from the solar water tanks are used instead of one draw-off level at a fixed position, the best position of the second draw-off level is for all the investigated systems in the middle or just above the middle of the tank.

3.2.1.2. Baffle plate. Baffle plate can effectively decrease the impingement and guide the direction of the coming fluid, and the mixing range of the turbulence will then be adjusted by baffle plate. In the work done by Shah and Furbo [66], the impact of the inlet design with different baffle plates on the flow patterns in the tank are numerically investigated and validated by experiments. A raw pipe, hemispherical baffle plate and a large flat baffle plate are compared under different discharge time and flow rate. It was shown that at lower flow rate, the cold water drops down to the

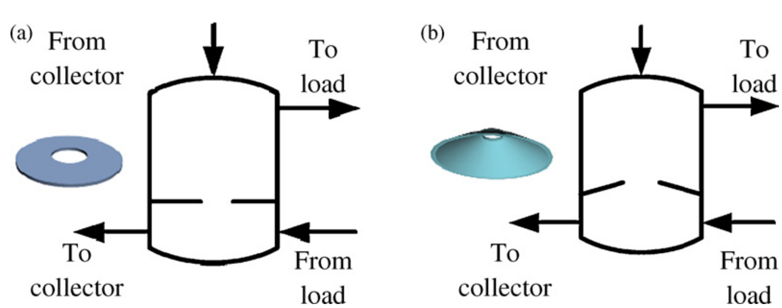

Fig. 8. Structure design comparison between the two types of baffle plate [40]: (a) flat plate obstacle type with central hole and (b) cone plate obstacle type with central hole.

bottom of the tank without creating any severe mixing, when the flow rate is increased by 10 times, the plume is almost half way up in the tank with the simple pipe. The small hemispherical baffle plate can break down the plume, and with the flat baffle plate, the flow raises steadily in the tank in the annulus between the tank wall and the flat baffle plate. The flat plate inlet, as expected, has a better performance.

Impact on stratification of 12 different baffle plates have been obtained using both experimental and numerical methods [79]; the results indicate that placing obstacle in the tank provides better thermal stratification compared to the no obstacle case. The obstacle types having gap in the center appear to have better thermal stratification than those having gap near the tank wall. The obstacle shapes and configurations (shown as in Fig. 8) for thermal stratification among the considered cases can supply hot water at higher temperatures, while other obstacle types have little effect on improving thermal stratification in the tank. Further comparisons of tank with flat plate and tank with cone plate in terms of the temperatures of hot water supply and cold water leaving the tank indicate that the cone obstacle provides the best thermal stratification in the tank among all the considered cases.

3.2.1.3. Thermal leakage. Experimental investigations by Shyu et al. [80] showed that thermal diffusion through the water in the tank is not a significant parameter causing decay of thermal stratification in vertical tanks. It was shown that degradation of thermal stratification in storage tanks with thicker walls are more pronounced due to larger axial heat conduction in the tank wall. It was concluded that the heat loss to the ambient was the major factor in degradation of the thermal stratification in an un-insulated tank, but the specific limit cannot be given in his research. From the investigations of Yee and Lai [81], heat loss from the tank can significantly degrade the thermal stratification. Thus, it should be minimized ($Bi \leq 1$) for a better performance of storage tank.

But in comparison with conclusions of Shyu and Yee, Nelson et al. [82] has studied the parameters affecting stratification within the tank, the material of the storage tank is found to have very little effect in the formation of thermo-clines during charging and discharging. The conclusion showed that in dynamic mode of operation, the effects of mixing overtake the influence of other parameters. However, the effect of wall material cannot be neglected in static storage systems wherein the tank is allowed to be idle with no inflow and outflows.

3.2.2. Operation condition

As Nelson analyzed, operation conditions such as static or dynamic mode are important issues and should also be investigated. Static mode represents the most frequent state of the tank and dynamic mode has great relations with real time analysis. So thermal behaviors of the tank in the operation periods need to be considered.

In previous studies to these investigations, Andersen and Furbo [83] showed that thermal de-stratification can cause a decrease in the net utilized solar energy by up to 23% due to mixing during draw-off, if 51% of the storage tank is mixed during each draw-off applied during the entire simulation. This mixing rate was found for measurements in a marketed solar tank carried out with an initial storage temperature of 30 °C at the bottom of the store and a flow rate of 0.33 l/s (20 l/min). Knudsen [31] showed that the net utilized solar energy of small solar heating systems decreases by about 10–16% if the storage tank is mixed in the lower 40% of the storage tank during each draw-off compared to the case that no mixing occurs, depending on the hot water tank design.

More systematic studies of Fernandez-Seara et al.'s [84] are centralized in operation mode. During static mode, results indicate that for the first stage of the cooling process following the heating with 2.2 kW, the stratification increases with respect to the stratification at the end of the heating process. Later on the stratification number slightly diminishes with a final value of 0.87. It points out that the decay of the stratification during this cooling process is very low. However, for the cooling process following the heating with heating power of 4 kW, the stratification decreases continuously during the cooling period. The analysis of the stratification reveals that it depends mainly on the initial water temperature profile. While in dynamic mode [85], three different inlet and two outlet ports for draw-off flow rates of 5, 10 and 15 l/min has been experimentally analyzed. Based on the considerations of maximum energy and exergy efficiencies, the optimal combination of inlet and outlet configure is determined among the different ports arrangements.

4. Performance of thermal stratification

4.1. Evaluating index

In order to assess the efficiency improvement on stratification, a standard should be lied down as a reference. Normally, for static condition, the normal parameters to evaluate performance are introduced as follows.

4.1.1. Stratification number

Stratification number is defined as the ratio of the mean of the temperature gradients at any time to the maximum mean temperature gradient for the discharging/charging process [84]:

$$\mathrm{Str}(t) = \frac{\overline{(\partial T/\partial z)_t}}{(\partial T/\partial z)_{\max}} \tag{9}$$

$$\overline{\left(\frac{\partial T}{\partial z}\right)_t} = \frac{1}{J-1}\left[\sum_{j=1}^{J-1}\left(\frac{T_{j+1}-T_j}{\Delta z}\right)\right] \tag{10}$$

$$\overline{\left(\frac{\partial T}{\partial z}\right)_{\max}} = \frac{T_{\max}-T_{\mathrm{in}}}{(J-1)\,\Delta z} \tag{11}$$

4.2. Energy efficiency

The energetic performance of the Domestic Electric Hot Water Storage Tank (DEHWST) is evaluated by calculating the thermal energy stored Q_{st} in the tank and the thermal energy lost [84]:

$$Q_{\mathrm{st}} = \sum_{j=1}^{J}\left|Q_j(t)\right| \tag{12}$$

$$Q_j(t) = (V\rho C_p)(T - T(t=0))_j \tag{13}$$

4.2.1. During heating process

The energy efficiency for the heating period is defined as the ratio of the energy available in the tank at any time to the energy supplied by the heating element until the instant considered [84]:

$$\eta_{\mathrm{h}}(t) = \frac{Q_{\mathrm{st}}(t)}{Q_{\mathrm{ele}}(t)} \tag{14}$$

$$\eta_{\mathrm{h,use}} = \frac{Q_{\mathrm{use}}(t)}{Q_{\mathrm{ele}}(t)} \tag{15}$$

And here $Q_{\mathrm{ele}}(t) = E{\cdot}t$, which means the total electric power generated during t time.

4.2.2. During cooling process

In the cooling period, the energy efficiency is referred to the energy accumulated in the tank at the beginning of the process [84]:

$$\eta_c(t) = \frac{Q_{st}(t)}{Q_{st}(t=0)} \tag{16}$$

$$\eta_{c,use} = \frac{Q_{use}(t)}{Q_{use}(t=0)} \tag{17}$$

4.2.3. During discharging process

The transient discharging energy efficiency is defined as the ratio of the cumulative thermal energy delivered by the water leaving the tank to the initial thermal energy stored in the tank [85]:

$$\eta_d(t) = \frac{Q_{out}(t)}{Q_{st}(t=0)} \tag{18}$$

$$Q_{out}(t) = \int_0^t (\rho V C_p)_{out}(T_{out} - T_{in})\,dt \tag{19}$$

$$Q_{st}(t=0) = \sum_{j=1}^{J}\left[\int_0^t (\rho V C_p)_j (T_j - T_{in})\,dt\right] \tag{20}$$

4.3. Exergy efficiency

The exergy analysis is particularly recommended since it accounts not only for energy stored but also for the temperature at which this energy is stored [45,86]. The exergy stored in the tank during the heating and cooling periods is calculated from the exergy of each discrete water layer considered in the analysis.

4.3.1. During heating process

The exergy efficiency for the heating period is defined as the ratio of the exergy accumulated at any time to that supplied by the electric heater until that moment:

$$\psi_h(t) = \frac{Ex_{st}(t)}{Ex_{ele}(t)} \tag{21}$$

$$\psi_{h,use}(t) = \frac{Ex_{use}(t)}{Ex_{ele}(t)} \tag{22}$$

4.3.2. During cooling process

In the cooling period, the exergy efficiency is referred to the exergy available in the tank at the beginning of the process [85]:

$$\psi_c(t) = \frac{Ex_{st}(t)}{Ex_{st}(t=0)} \tag{23}$$

$$\psi_{c,use}(t) = \frac{Ex_{use}(t)}{Ex_{use}(t=0)} \tag{24}$$

4.3.3. During discharging process

The transient discharging exergy efficiency is defined as the ratio of the cumulative exergy delivered by the water leaving the tank to the initial exergy stored in the tank [85]:

$$\psi_d(t) = \frac{Ex_{out}(t)}{Ex_{st}(t=0)} \tag{25}$$

$$Ex_{out}(t) = \int_0^t (\rho v)_{out}[(h_{out} - h_0) - T_0(s_{out} - s_0)]\,dt \tag{26}$$

$$Ex_{st}(t=0) = \sum_{j=1}^{J}\{(V\rho)_j[(u_j - u_0) - T_0(s_j - s_0)]\} \tag{27}$$

According to Fernandez-Seara et al.'s research [83,85], the heating energy efficiency is high with values over 85%. The heating useful energy efficiency is mainly affected by the initial water temperature. The exergy efficiencies of the heating processes are very low (around 5%). Experimental results show that the cooling processes are mainly influenced by the ambient temperature.

4.4. Dimensionless group analysis on stratification

The efficiency of a stratified storage tank is closely related to the dynamic behavior of thermal stratification inside the tank. It was found that the system flow rate, the inlet water temperature and the inlet flow pattern are the main factors to control the initial formation and subsequent behavior of stratification. By comparing analytical predictions with experimental measurements, in earlier studies, many researchers turned to dimensionless coefficients that include so many original parameters on stratification, from the comprehensive variations, much information involving tank dimensions, flow velocities, and structural designs etc can be developed to characterize the levels of mixing and many thermodynamics parameters. These parameters could be exam-

Table 2
Earlier research on parameters impaction on stratification

Author	Year	Parameter consideration	Conclusions	Stratification
Lavan and Thompson [4]	1977	Flow factor (based on Reynolds number, Grashof number, tank height diameter ratio)	Above 40–50	Almost no mixing occurred
Zurigat et al. [42]	1990	Richardson number	$Ri < 3.6$	Inlet geometry has great influence on stratification
Ghajar and Zurigat [43]	1991	Richardson number	$Ri > 10$	Inlet effect can be neglected
Yoo and Pak [54]; Al-Nimr [53]	1993	Peclet Number	At high Peclet	Stratification less apparent
Cai and Stewart [59] and Sohn	1993	Archimedean number and Reynolds number	$Ar > 5$ and $Re < 1000$	The cold fluid will not extensively mix with the warmer fluid
van Berkel et al. [87]	1999	Richardson number	$Ri > 10–20$	Clear mixing appearing
Ramsayer [88]	2001	Richardson number	$Ri > 0.2$	Mean temperature gradient is not influenced by the inlet flow
Stewart and William [89]	2001	Froude number and Reynolds number	$Re = 6000$	Not result in a significantly thermo-cline
Brown and Lai [14]	2004	Richardson number	$Ri = 0.615$	Stratification is observed

Table 3
Classifications on research of thermally stratified water tank

Structure design	Numerical simulation	Experimental test	Performance analysis	New applications
Conventional	Models	Flow visualization	Cost economies	DHW
With confinement (net mesh, porous or baffle plate, etc.)	Analytical methods	Parameter analysis	Energy analysis	ICS
Partition	CFD software	Structure design	Entropy generation	Heat storage
	TRNSYS		Exergy analysis	

ined in terms of dimensionless groups such as the inlet Reynolds number, the Froude number (*Fr*) the tank Reynolds number, the Peclet number and the Richardson number. According to most previous investigations on normal storages, the impaction on thermal stratification of inlet geometry parameters is listed in detail in Table 2.

From Table 2, it can be found that Richardson number (*Ri*) plays an important role in characterizing the levels of mixing in the tank storage, by comparing analytical predictions of different studies, researchers have inconsistent range about *Ri* number impacting on mixing. From Zurigat's results, for $Ri > 10$, thermal stratification keeps constant without the consideration of inlet geometry, while when $Ri < 3.6$, the effect of inlet geometry cannot be neglected. Berkel found that it was clear that mixing in the experiment was insignificant for $Ri \geq 10$–20. While the conclusions of Ramsayer show that when $Ri > 0.2$, the mean temperature gradient is not influenced by the inlet flow, the limitation is lower than that of Zurigat's research, but as is close to the results of Brown whose analysis showed stratification can still be observed when *Ri* number is of 0.615. On all accounts, Shah and Furbo [66] investigated the entrance effects in solar storage tanks, the result showed the entropy changes and exergy changes in the storage during the draw-offs influenced by the Richardson number and initial conditions.

5. New development on thermal stratification

5.1. Classification and recent research

According to the recent studies mentioned above, thermal stratification within the water tank is gradually being paid more attention in actually applications. In general, the wide variety of researches and function indications of thermally stratified water tank known today makes it possible to perform their classifications, which are given in Table 3.

Thermal storage tanks are widely extended in solar systems, achieving effective thermal stratification within the tank storage is essential to ensure the whole system of solar utilizations such as SDHW, thermal energy storage (TES), ICS, etc., while the heat capacity and the level of temperature stratification, which related to the quality of the energy stored are especially focused permanently.

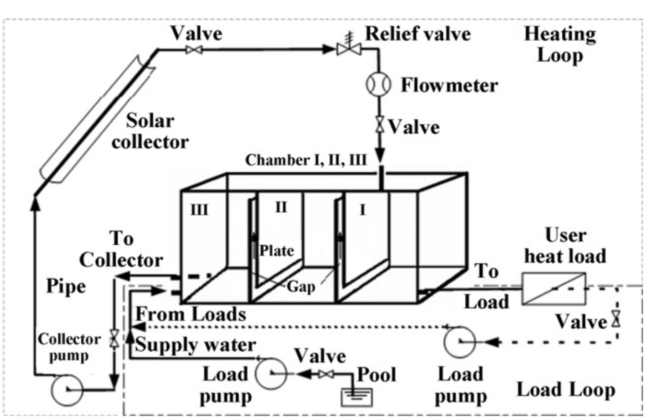

Fig. 9. Horizontally partitioned water tank with thermal stratification used in large-scale solar powered system (studied in SJTU).

As solar domestic hot water system be concerned, in commercial system, Arata and de Winter [90] used multiple tanks for solar energy storage in order to enhance the stratification effect, baffle plate was used several years ago [91,92]; many others studied stratification effects based on realistic SDHW consumption behavior. From the studies mentioned above, good fluid dynamics computer models and programs are developed and optimized with the time lasts. Stratification effectiveness within the tank can be verified and improved by further research in the future.

For diurnal TES used by other working mediums such as solid–liquid PCMs are more expensive, water and ice will continue to the dominant technologies in thermal energy storage, the temperature distribution optimizations within water and ice thermal storage tank are mainly focused on structure design and fluid dynamic analysis. The theoretical models and numerical simulations will be taken into account in the future, the necessity of increasing the accuracy, refining the meshes employed and improving the computing methods and codes, the introduction of multi-block and parallel computing will be the tendencies on decreasing the high cost for three-dimensional simulations at present [93].

5.2. Thermal partition research in SJTU

Here, introduction of a kind of horizontally partitioned water tank being studied in SJTU is presented, the tank with partitioned structural design is particularly used for large-scale solar energy system in buildings (as shown in Fig. 9), because it can be installed in a limited space and have good performance in both energy storage and thermal stratification. With the cooperation by United Technologies Research Center (UTRC), America, both experimental study and numerical analysis are investigated on the effect of energy storage and thermal stratification under various operation conditions. It is found that this kind of tank can effectively inhibit transverse heat transfer, and the gap between the insulation plates plays an important role in effecting the thermal stratification and preventing the effect of transverse heat transfer. When the temperature difference of the inlet and the outlet is steadily kept at 70 K, the temperature decline of each chamber along the horizontal partition can be maintained at 15–20 K, and these characteristics between chambers is kept constant even when *Ri* number is less than 10^{-2} level.

6. Conclusions

Due to the inhibition of mixing between different temperature layers, thermal stratification within the water tank can effectively improve the exergy and the utilization efficiency of whole solar system. To maintain the stable thermal stratification is to keep temperature gradient or thermo-cline, so static heating, hot water in-draft at suitable height or by heat exchanger.

For immersed exchanger, the inner arrangement of exchanger and type of conduct pipe significantly affect the stratification along

the store height, heat exchanger position should be coiled upwards and located in the upper part of the tank. While for external exchanger, it may be more practical and less mixing, but the heat exchanger performance is evaluated in terms of the natural convection flow rate. Mantle exchanger outperforms the two former types. It is found that a vertical mantle heat exchanger can promote stratification in the tank even when the mantle inlet temperature is lower than that at the input.

Thermal performance of direct heat transfer is definitely affected by multiple factors such as geometrical structure and operating condition. Related discussions in detail are introduced from model analysis and commercial software. Two-dimensional models can take the mixing between layers into account, which includes more factors than that of one-dimensional level.

The influencing factors consist of inlet and outlet condition, baffle plate, thermal leakage, static or dynamic operating conditions. Dimensionless group analysis show that Richardson number is generally used as the evaluate index, and this value can be deceased to lower than 0.2 to maintain the thermal stratification within the tank. Performance of thermal stratification is determined by different evaluating index as stratification number, energy efficiency, or exergy efficiency.

Further research in thermal stratification will focus on enhancement of temperature gradient between layers. In order to attain the reliable backup provisions and a very high solar fraction, it is necessary to find new design of tank structure to improve calculation methods and to build new models include more microscopic mechanism, and the productive equipment structural designs, water consumption behaviors, whole system research and design, and evaluation will become serious in the later considerations.

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